DISCOVERY OF NEW DWARF GALAXY NEAR THE ISOLATED SPIRAL GALAXY NGC 6503

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ABSTRACT

We report the discovery of a new dwarf galaxy (NGC 6503-d1) during the Subaru extended ultraviolet (XUV) disk survey. It is a likely companion of the spiral galaxy NGC 6503. The resolved images, in the B, V, R, i, and Hα bands, show an irregular appearance due to bright stars with underlying, smooth and unresolved stellar emission. It is classified as the transition type (dIrr/dSph) between the dwarf irregular (dIrr) and dwarf spheroidal (dSph) types. Its structural properties are similar to those of the dwarfs in the Local Group, with an absolute magnitude $M_{\rm V} \sim -10.5$, half-light radius $r_{\rm e} \sim 400\,{\rm pc}$, and central surface brightness $\mu_{0,{\rm V}} \sim 25.2$. Despite the low stellar surface brightness environment, one H II region was detected, though its Hα luminosity is low, indicating an absence of any appreciable O-stars at the current epoch. The presence of multiple stellar populations is indicated by the color-magnitude diagram of ~ 300 bright resolved stars and the total colors of the dwarf, with the majority of its total stellar mass $\sim 4 \times 10^6 {\rm M}_\odot$ in an old stellar population.

Subject headings: galaxies: dwarf — galaxies: individual(NGC 6503) — galaxies: irregular — galaxies: stellar content

1. INTRODUCTION

Dwarf satellite galaxies provide vital guidance for understanding star formation (SF) and galaxy evolution, and their discovery and structural analysis are of broad interest. They often have extremely low surface brightness (LSB) and exhibit rare instances of SF in the low-density environments. They are potential triggers of SF in their more prominent parent galaxies. The observed statistics and internal structures of dwarf satellites in the Local Group are challenging the ΛCDM scenario (Klypin et al. 1999; Moore et al. 1999; Boylan-Kolchin et al. 2012). Systematic searches for dwarf satellites around other galaxies, including a more rigorous one in the Local Group, are being undertaken (e.g., McConnachie 2012; Monachesi et al. 2014; Merritt et al. 2014; Sand et al. 2014; Tollerud et al. 2014; McQuinn et al. 2015, Donovan Meyer et al. submitted).

In this Letter, we report the discovery of a new dwarf galaxy NGC 6503-d1, approximately 17′ away from the spiral galaxy NGC 6503. NGC 6503 is comparatively isolated at the edge of the Local Void (Karachentsev et al.

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2003; Greisen et al. 2009). It is an SA(s)cd type spiral galaxy at a distance of d=5.27 ± 0.53 Mpc (1″ = 25.5 pc; Karachentsev et al. 2003) with a heliocentric velocity of $v_{\rm h} = 25 \pm 1\,{\rm km\,s^{-1}}$ (Epinat et al. 2008). NGC 6503 has a major axis of $D_{25} \sim 10.9\,{\rm kpc}$ (7.1′) and an absolute magnitude of $M_{\rm V} = -19.07$ (calculated from de Vaucouleurs et al. 1991). Assuming a mass-to-light ratio $\gamma_{\rm V} \sim 1.2$ (see McGaugh & Schombert 2014), NGC 6503's stellar mass is $\sim 4 \times 10^9 {\rm M}_\odot$, and its virial radius is approximately 150 kpc (see Kravtsov 2013). We present the basic properties, stellar populations, and recent SF activity of the new dwarf galaxy NGC 6503-d1. Uncertainty still remains as to the distance of NGC 6503-d1, but based on its proximity and other supporting evidence the dwarf is most likely associated with NGC 6503.

NGC 6503 shows very extended ultraviolet emission far beyond the edge of its optical disk (Thilker et al. 2007). Such extended ultraviolet (XUV) disks indicate SF at a very low density (Koda et al. 2012) and are quite common (residing in ~30% of nearby galaxies; Thilker et al. 2007). However, the trigger of the XUV activity still remains unknown (e.g., Espada et al. 2011). NGC 6503-d1 is the first dwarf satellite discovered during the early observations of the Subaru-XUV survey, a deep optical imaging survey of nearby XUV disks using the Subaru telescope.

2. OBSERVATIONS AND DATA REDUCTION

The dwarf galaxy was discovered in deep imaging of the spiral galaxy NGC 6503 using the the Subaru Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) on the Subaru telescope. Suprime-Cam has a mosaic of ten 2048×4096 CCDs, covering a wide field of $34' \times 27'$ with a pixel scale of 0.20″. The observations were performed in June and July 2013 and supplemented with archival data taken in July 2012. The field of NGC 6503 was observed in the B, V, R, i, and NA656 (Hα) bands, among which the images in V and i were deeper. The typical seeing

was 0.8″.

The data were reduced in a standard way, including an overscan correction, masking of the shadow of the autoguider probe, flat-fielding, and distortion correction before co-adding all exposure frames (Yagi et al. 2002). Photometric calibrations were performed using a catalog from the Panoramic Survey Telescope & Rapid Response System 1 (Pan-STARRS 1; Magnier et al. 2013; Schlafly et al. 2012; Tonry et al. 2012). We followed the procedure described in Yagi et al. (2013) and converted from the Pan-STARRS 1 to the Subaru band system using stellar photometry. Typical photometric errors including both statistical and systematic effects are $\lesssim 0.1$ mag.

We also obtained archival FUV and NUV images from the Galaxy Evolution Explorer (GALEX). We averaged two available data sets from the GALEX Nearby Galaxies Survey (NGS; Gil de Paz et al. 2007) and from the General Investigator Program (GI1 Program 097).

3. DISCOVERY AND CLASSIFICATION

Figure 1 shows the new dwarf galaxy NGC 6503-d1. The BVR color image (panel a) shows a lopsided distribution of resolved bright stars in the northern part of the dwarf, apparently indicating an irregular morphology. However, we also found a smooth, extended, and symmetric stellar distribution in logarithmic scale (panel c; V band example), which is perhaps a more accurate representation of the stellar mass distribution. Panel (e) shows the continuum-subtracted Hα image. Hα emission is detected at one spot within the dwarf. The presence of the resolved bright stars and the H II region indicate that this dwarf hosts recent/current SF and, by implication, some gas, though no HI gas was detected at the 3σ upper limit of $< 10^6 M_\odot$ (Greisen et al. 2009).

We classify this as a transition-type dSph/dIrr, based on traditional definitions (Tolstoy et al. 2009; McConnachie 2012), the type between dwarf irregular (dIrr) and dwarf spheroidal (dSph). We note, however, that there is a discussion on whether dIrrs and dSphs are physically distinct, the only difference being their current/recent SF which outshines the other populations and gives the impression of an irregular morphology (e.g., Weisz et al. 2011).

4. PROPERTIES

NGC 6503-d1 is very likely a satellite galaxy of NGC 6503. Their projected separation $\sim 17'$ is well inside NGC 6503's virial radius $\sim 100'$ (~ 150 kpc), suggesting a high probability of their physics association ($> 80\%$) based on N-body simulations (e.g., Tollerud et al. 2011). The Hα detection also supports its proximity to NGC 6503, though the heliocentric velocity of NGC 6503 ($v_h = 25\pm1$ km s^{-1}) is very close to MW's and it is difficult to distinguish between NGC 6503 and the MW. Although uncertainty still remains, we assume that the dwarf is a companion of NGC 6503 in what follows. We will discuss a few pieces of supporting evidence in addition to the proximity, including its size and magnitude (distance-dependent parameters) compared to other dwarf galaxies (§4.2) and a likely detection of the tip of red giant branch (TRGB) star population (§4.3). Each of these alone is insufficient to prove that the dwarf is a satellite of NGC 6503.The combination, however, supports our working assumption, that $d = 5.25$ Mpc is the

TABLE 1
Properties of NGC 6503-d1

Parameter	Value
Distance-independent Properties	
R. A. (J2000)	17:52:48.4
DEC (J2000)	+70:08:14.4
Galactic longitude l (degree)	100.5403
Galactic latitude b (degree)	30.3563
V_h (km s^{-1})	~ 0
FUV (AB mag)	21.1
NUV (AB mag)	20.4
B (AB mag)	18.5
V (AB mag)	18.1
R (AB mag)	17.8
i (AB mag)	17.6
Sersic index n	0.54
$\mu_{0,V}$ (AB mag arcsec^{-2})	25.2
r_e (″)	15.6
Axis ratio	0.61
P. A. (deg, N to E)	-2.6
Distance-dependent Properties	
m-M (mag)	28.61±0.23
d (Mpc)	5.27±0.53
M_{FUV} (AB mag)	-7.6
M_{NUV} (AB mag)	-8.2
M_B (AB mag)	-10.1
M_V (AB mag)	-10.5
M_R (AB mag)	-10.8
M_i (AB mag)	-11.0
r_e (pc)	400
$F_{H\alpha}$ (erg s^{-1})	8.2×10^{35}
Stellar mass (M$_\odot$)	$\sim 4 \times 10^6$
HI gas mass (M$_\odot$)	$< 10^6$

All magnitudes are corrected for Galactic extinction. Typical errors due to photometric calibration and background contamination are ~ 0.14 mag.

distance to NGC 6503-d1.

4.1. Internal Structure

The GALFIT package (Peng et al. 2002) was adopted to measure structural parameters of the dwarf. The fit was made to the V band image with a Sersic profile (Sersic 1968) and fixed sky background after removing some surrounding stars. We obtained a Sersic index of $n = 0.54$ with $\chi^2_\nu = 2.8$ ($\nu = 90494$). This result was consistent with that using the i band image. As noted earlier, some bright stars within the dwarf outshine the underlying smooth stellar distribution. After aggressively masking these we obtained $n = 0.63$ ($\chi^2_\nu = 0.63$) though it is debatable whether the member stars of the dwarf should be masked out. Table 1 gives properties of NGC 6503-d1, including its central coordinates, axis ratio, position angle (P. A.), and effective radius/half-light radius r_e, as well as other global parameters. The central surface brightness μ_V was derived from the value at the central pixel of the fitted model, and the result after Galactic extinction correction, $\mu_V = 25.18$ mag arcsec^{-2}, is typical for dwarf galaxies (McConnachie 2012).

Apparent magnitudes (AB magnitude) were calculated within an elliptical aperture (Figure 1). The shape of the aperture was derived from GALFIT (i.e., an axis ratio and P. A.) with the major axis diameter scaled to 34″ so as to enclose the emission of the dwarf. The fluxes of foreground/background contamination were es-
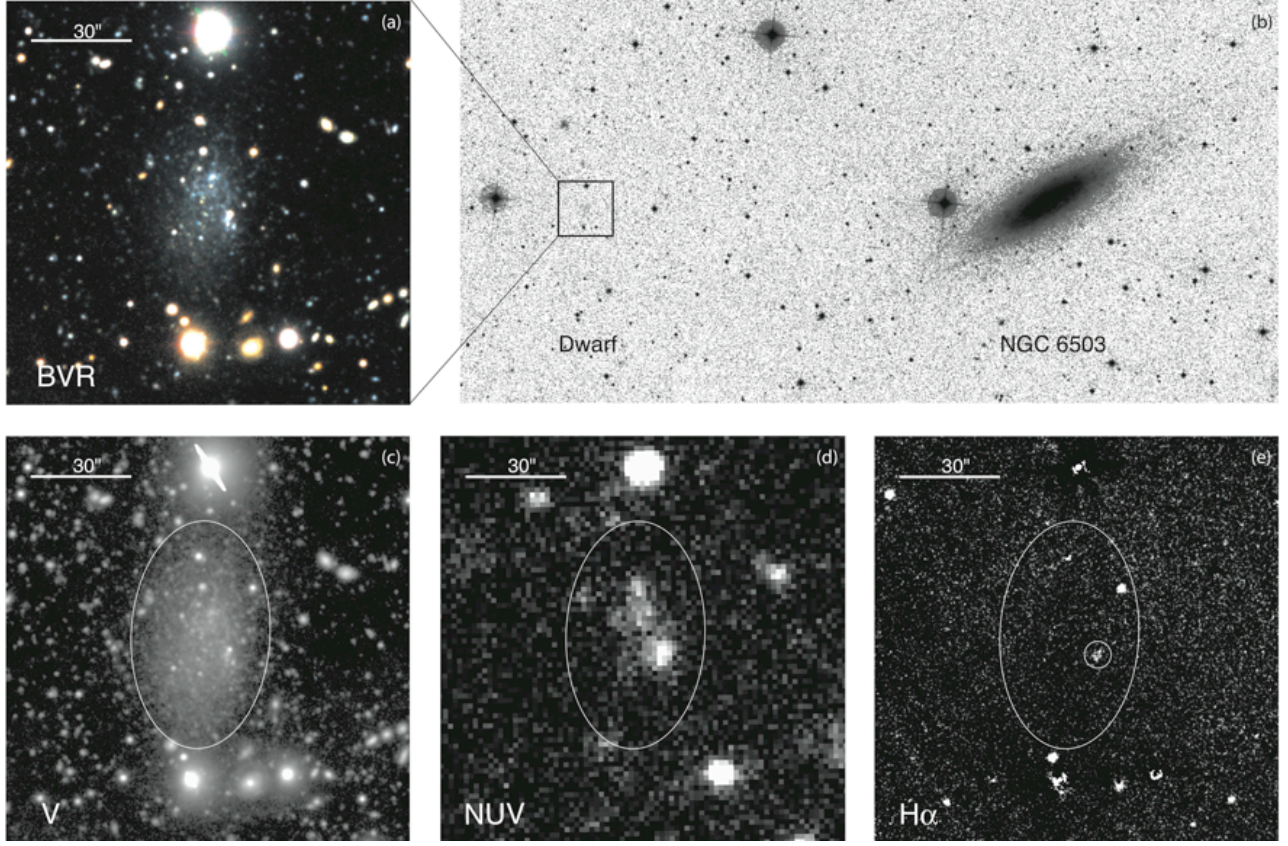
FIG. 1.— Subaru images of $2' \times 2'$ region around the dwarf, except at top-right, which is a $\sim 30.2' \times 12.7'$ region from the Digitized Sky Survey (DSS). North is up, and east is left. The photometric aperture is an ellipse with a major axis of $\sim 68''$, axis ratio of 0.61, and position angle of -2.6 deg from north to east. (a) Pseudo color image with Subaru B, V, and R. (b) DSS image of NGC 6503 and the new dwarf galaxy. (c) Subaru V band image in log scale. (d) GALEX NUV image. (e) Subaru Hα image (net Hα). The small circle encloses the identified H II region.

timated by placing the apertures in the surrounding region. We subtracted their averages from the fluxes within the dwarf aperture and adopted their typical scatters of 0.1 mag as errors in photometry. The apparent magnitudes are listed in Table 1. We adopted a Galactic extinction of $A_V = 0.106$ (Schlegel et al. 1998; Schlafly & Finkbeiner 2011) and calculated extinctions in UV and NA656 with $(A_{FUV}, A_{NUV}) = (2.58, 2.83)A_V$ for the Milky Way (Koda et al. 2012) and $A_{NA656} = A_R$. These aperture magnitudes were consistent with the ones from GALFIT (e.g., 18.2 mag in V).

4.2. *Statistical Properties*

If it is a satellite of NGC 6503, NGC 6503-d1 lies within the sequence of dwarf galaxies in the Local Group, in surface brightness μ_V, absolute magnitude M_V, and half-light radius r_e. Figure 2 shows their correlations with Local Group dwarfs (McConnachie 2012) and Galactic globular clusters (Harris 1996) as references. The new dwarf is distinct from the globular clusters and lies midway between dIrrs (blue) and dSphs (yellow) and among the dIrr/dSph transition types (green). This location is consistent with the visual appearance of the dwarf, having apparent irregular morphology (due to recent SF) with the more symmetric morphology of the underlying stellar population.

The Sersic profile of $n = 0.54$ is also within the range typical of dwarf galaxies of similar brightness. Radial profiles of dwarfs are often fit with an exponential profile

(an $n = 1$ profile; e. g., Ibata et al. 2007; Richardson et al. 2011; Crnojević et al. 2014), though $n = 0.3$-0.7 has been reported for dwarf galaxies around M101 (Merritt et al. 2014) and an isolated dwarf galaxy (Monachesi et al. 2014). Geha et al. (2006) showed a spread of $n \sim 0.5$-1.5, albeit among brighter dwarfs ($\lesssim -14$ mag). The structural properties of the new dwarf are, therefore, typical of faint dwarf galaxies in the Local Group and in some other nearby systems.

4.3. *Resolved Stars*

The high spatial resolution of the Subaru images ($\sim 0.8''$) permits identification and photometry of individual bright stars within NGC 6503-d1. We made an initial catalog of 312 potential detections using the DAOPHOT PSF photometry software (Stetson 1987). We then manually rejected apparent misidentifications (e.g., background galaxies and tails between adjacent bright stars), leaving 303 stars, which are identified in Figure 3a. We performed photometry in V and i bands, made a color-magnitude diagram (CMD; *middle*) and a histogram of apparent i magnitude for stars with $V - i > 0.6$ (*right*).

Theoretical isochrones are superimposed on the CMD assuming a distance of NGC 6503 ($m - M = 28.62 \pm 0.23$) and were taken from the Padova and Trieste stellar evolutionary tracks (Bressan et al. 2012; Chen et al. 2014; Tang et al. 2014)[9]. The red isochrones are at an age
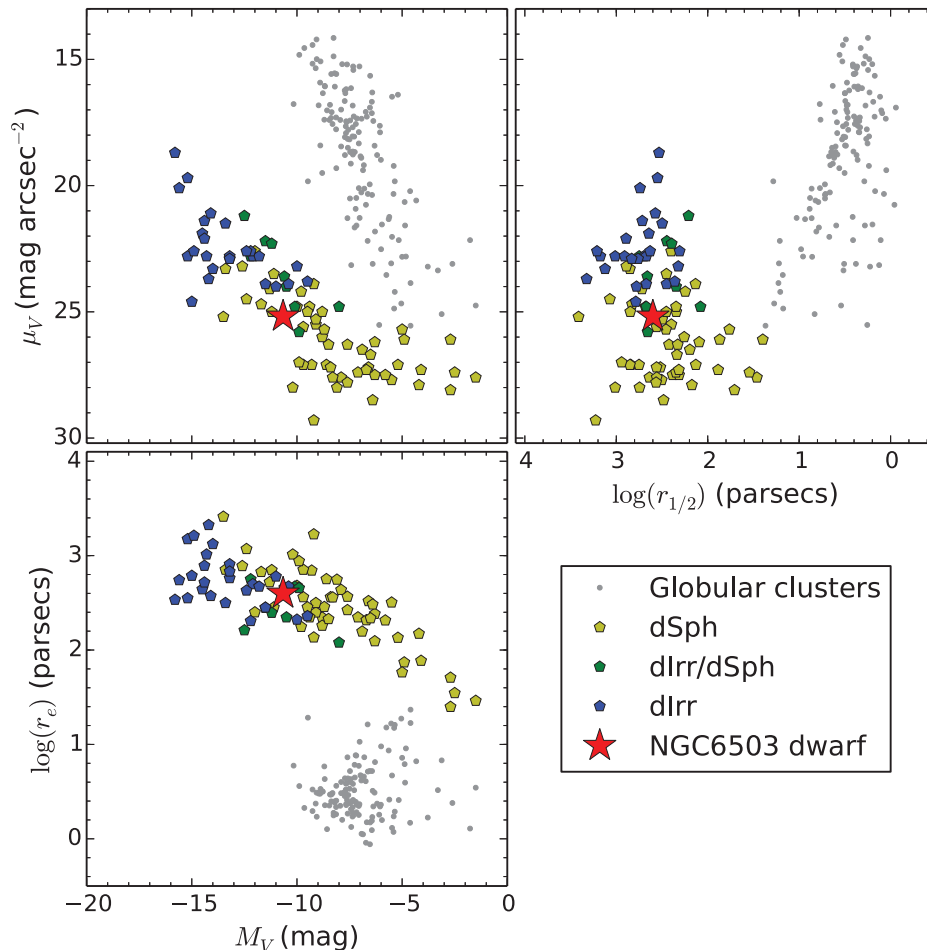
[9] http://stev.oapd.inaf.it/cgi-bin/cmd

Fig. 2.— Correlations between central surface brightness $\mu_{\rm V}$, half-light radius $r_{\rm e}$, and absolute V magnitude $M_{\rm V}$. The red star is the new dwarf galaxy. Comparison data are dwarf spheroidal (dSph), dwarf irregular (dIrr), and transition (dIrr/dSph) galaxies in the Local Group compiled by McConnachie (2012) and Galactic globular clusters from Harris (1996). We adopted the distance of NGC 6503 for NGC 6503-d1.

of 10 Gyr for metallicities of $\log(\mathrm{Z}/\mathrm{Z}_\odot) = $ -2.0, -1.5, -1.0, and -0.5 from the left to right. The others are for $\log(\mathrm{Z}/\mathrm{Z}_\odot) = $-0.5 and at $\log(\mathrm{Age[year]})$=7 to 10 (see legend). The bright stars that we identified are around the areas of the asymptotic giant branch (AGB), horizontal branch (HB), and red giant branch (RGB) sequences. Therefore, the dwarf hosts multiple stellar populations, from young (∼100 Myr, cyan isochrone) to old (≳8-10 Gyr, magenta and red). Many stars in the recently formed population must have escaped their natal dust given the agreement between unreddened isochrones and our photometry, especially regarding the blue limit of the He-core-burning population. The RGB sequence depends on stellar metallicity (red lines; see also Lee et al. 1993). The spread on the red side may indicate a variety of metallicity in the underlying stellar population.

The tip of RGB (TRGB) stars are often used as a distance indicator, as their luminosities are approximately constant near the i band wavelength (Lee et al. 1993). By averaging the four red isochrones in Figure 3b we determined a TRGB magnitude of $M_i = -3.53$ AB mag in the Subaru i band. If the dwarf is a companion of NGC 6503, the corresponding apparent magnitude is $m_i = 25.09$ with an error of at least ± 0.23 carried over from the distance modulus. Within the errors, this is roughly where we see the rise in the histogram (Figure 3c; $V - i > 0.6$

for TRGB color), though the sample is small. This supports the assumption that the dwarf is a companion of NGC 6503.

4.4. Star Formation History

The central and average V band surface brightnesses are 25.18 and 26.31 mag arcsec^{-2}, respectively, after correcting for the Galactic extinction. Any SF there is a rare incident in a very LSB regime. Conventionally, galaxies sizes have been defined by the 25 mag arcsec^{-2} isophote level. The distribution of resolved stars in the CMD suggests multiple stellar populations, indicating that SF has persisted for a long period of time. Figure 1e shows the detection of one H II region (small circle) within the dwarf at 6σ significance. The H II region is virtually co-incident with the brightest spot in NUV (GALEX J175247.4+700811; Figure 1d), indicating current SF in this LSB galaxy. [The brightest Hα spot at NW without NUV emission is unlikely to be in the dwarf, since it would be too bright.]

The SF activity of this H II region is low, which is inferred from its faint Hα luminosity of $L_{\rm H_\alpha} = 8.2 \times 10^{35}$ erg s^{-1}. This was measured within an 8″-diameter aperture centered at $(\alpha_{\rm J2000}, \delta_{\rm J2000}) = (17{:}52{:}47.1, +70{:}08{:}09.8)$ with correction for Galactic extinction. The uncertainty is about a factor of 2 due to
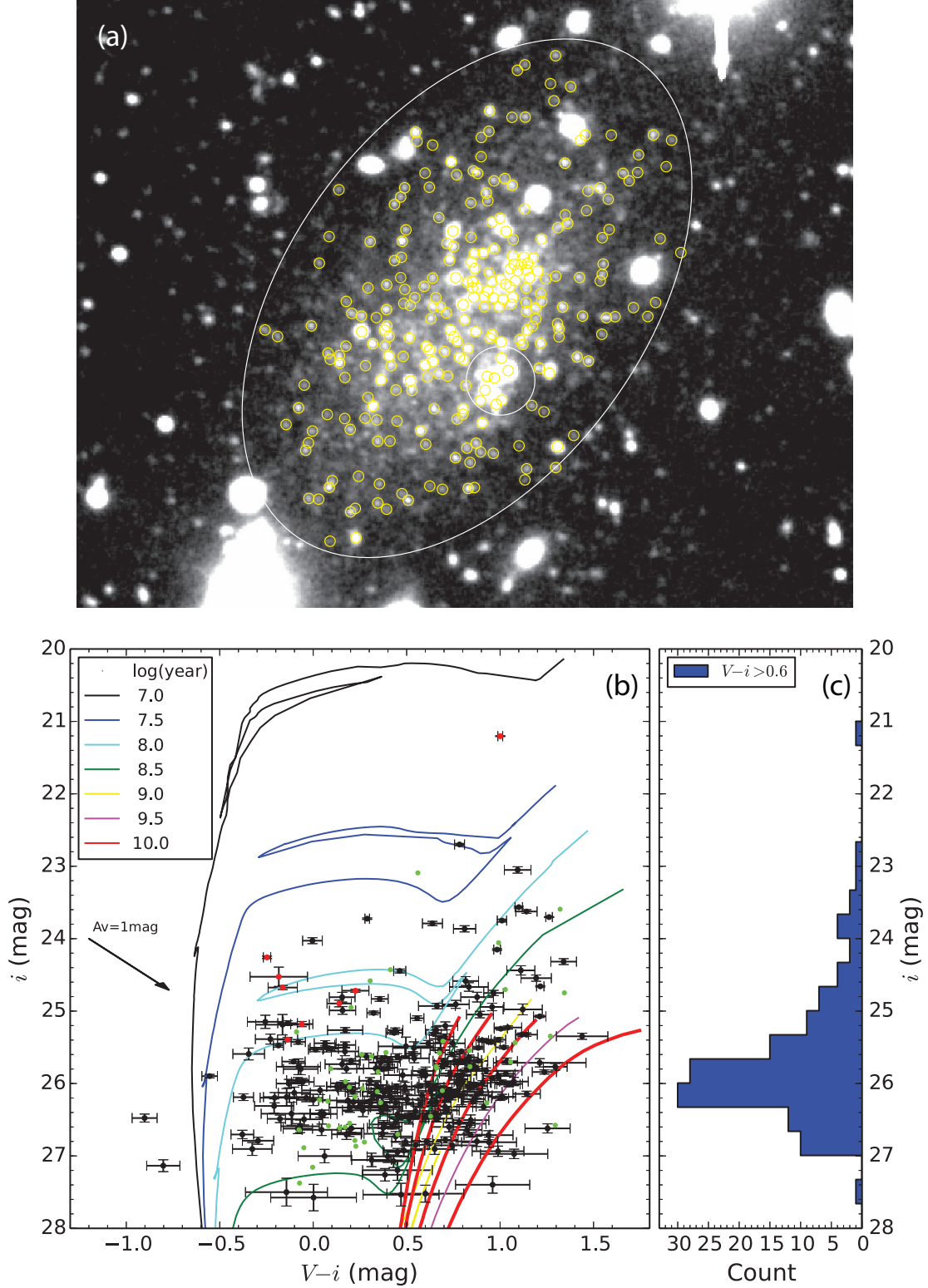
FIG. 3.— Analysis of resolved stars. (a) Locations of resolved stars (yellow circles) in i band image. The image orientation is not rotated from the original to maintain the high spatial resolution. The while ellipse and circle (HII region) are the same as the ones in Figure 1. (b) Color-magnitude diagram (CMD) with V and i bands. The stellar isochrones are from the Padova evolutionary tracks (CMD 2.7) and of $\log(Z/Z_\odot) = -0.5$ at $\log(\text{Age}) = 7.0$, 7.5, 8.0, 8.5, 9.0, 9.5, and 10.0. The red isochrones are of $\log(\text{Age}) = 10.0$ for $\log(Z/Z_\odot) = $-2.0, -1.5, -1.0, and -0.5 from left to right, respectively. We applied the distance modulus of NGC 6503 ($m - M = 28.62 \pm 0.23$). Stars within the HII region aperture (white circle in panel (a)) are marked red. For comparison, the green dots are objects in a control field of the same size about $2'$ away from NGC 6503-d1 (at the same distance from NGC 6503); these background objects are populated much more sparsely in the CMD (this is so, even though the difference in confusion limit is not corrected). (c) Histogram of apparent i band magnitude for all identified stars of $V - i > 0.6$. The increment is 0.33 mag. From the bright to faint, the number starts increasing between the bins of $m_i = 25.17$ and 25.50. The AB magnitude of TRGB in Subaru i is approximately -3.53 (absolute) and 25.09 ± 0.23 (apparent; see the text).

a sensitivity to continuum subtraction (The fraction of Hα over total emission in the NA656 band is ∼5% in the aperture). The contamination of [NII] λ 6548, 6583 emission is likely negligible (see Kennicutt et al. 2008). This L_{H_α} is on the order of that expected around a single B0V type star ($\sim 7.0 \times 10^{35}\,\mathrm{erg\,s^{-1}}$ under case B recombination with an electron temperature of 10^4 K; Sternberg et al. 2003; Osterbrock & Ferland 2006; Koda et al. 2012). This is consistent with observations of the Orion Nebula in the Milky Way, which is about 10 times brighter in L_{H_α} with only a single O5.5V type star as a dominant ionizing source. The second brightest stars in Orion (one O9.5V, two B0.5V, and one B3; Reipurth 2008) together emit ∼ 10-20 times fewer Lyman continuum photons (e.g., Sternberg et al. 2003). Therefore, the dwarf galaxy is unlikely to be hosting any appreciable O-star population at the current time, assuming that the leakage of ionizing photons is not dominant ($\gtrsim 90\%$ of the Lyman continuum photons need to leak away without ionizing the surrounding gas to hide an O-star). Of course, it could have had O-star(s) a short time ago as their lifetimes are short (~ 10 Myr). The stars around this HII region are AGB and blue loop stars (Figure 3). One, or some, of these may be the ionizing source if an internal extinction is locally large ($A_V \sim 1$).

The observed colors of the dwarf (Table 1) also indicate multiple epochs of SF. Rigorous analyses of SF history (e.g., Weisz et al. 2011, 2012) are beyond our scope, and a dwarf galaxy of small mass requires stochasticity in SF to be taken into account (e.g., da Silva et al. 2012). Instead, we adopt a simplistic approach to illustrate that at least two stellar populations, old and young, are necessary to account for the observed colors, and that most of the stellar mass is old. We adopted Starburst99 (Leitherer et al. 1999), a Kroupa initial mass function, a metallicity of $Z = 0.4Z_\odot$, and an internal extinction $A_V = 0.1$ for the integrated colors of the dwarf. These choices were made arbitrarily for demonstration; for example, the metallicity may have a range from a low $\log(Z/Z_\odot)$ up to > -0.5 according to Figure 3 (the data with respect to the RGB isochrones).

Figure 4a shows that neither a model of single starburst at any age nor continuous SF alone reproduces the FUV-NUV and V-i colors simultaneously unless A_V is unusually high. Figure 4b shows an example of stellar populations at the young and old ages of 300 Myr and 12 Gyr. The young population (blue) is relatively bright in FUV and NUV and shows a flat spectrum in the redder, optical range (B, V, R, and i). The old population (green) contributes negligibly in the FUV and NUV and shows a rising spectrum in the optical bands. The dwarf is relatively bright in FUV and NUV (requiring a young stellar population) and shows a rising trend in the optical bands (old stellar population). The masses of stellar populations determine the zero point in magnitudes: the old component carries the most mass ($\sim 3.6 \times 10^6 M_\odot$; insensitive to the actual age if $\gtrsim 8$ Gyr) as compared to the young one ($\sim 2.8 \times 10^5 M_\odot$). The total stellar mass within the dwarf is approximately $4 \times 10^6 M_\odot$.

5. SUMMARY

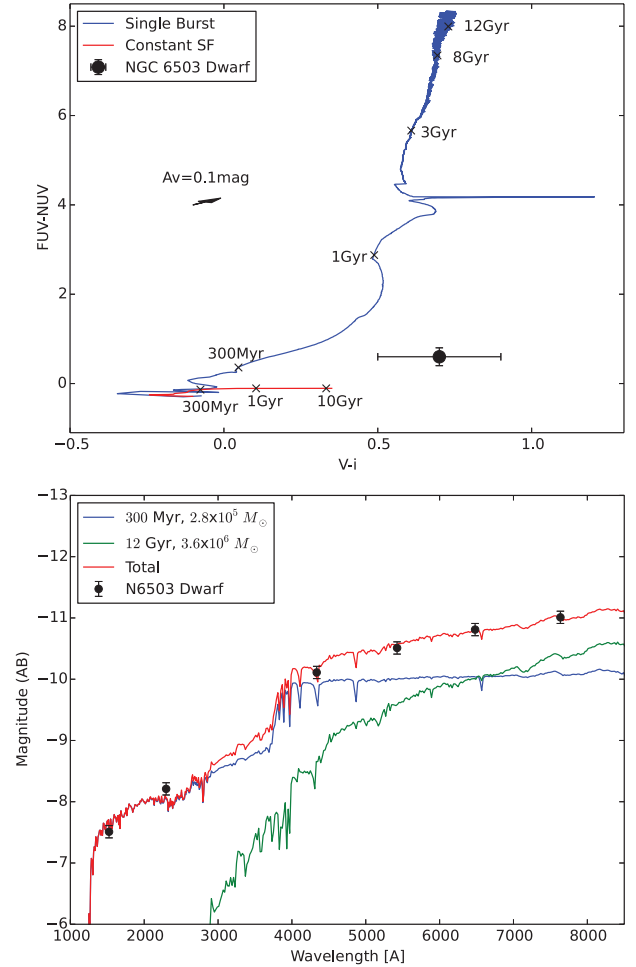We have discovered the new dwarf galaxy of the dIrr/Sph transition type, NGC 6503-d1, which is likely

FIG. 4.— Comparisons of photometric evolution models (Starburst99) and the data for the dwarf. A metallicity of $0.4Z_\odot$ and a Kroupa initial mass function are adopted. (a) FUV-NUV vs V-i plot. A single burst model (blue) and constant SF model (red) are plotted. The arrow shows an internal extinction of $A_V = 0.1$ mag using the extinction curve of LMC (Pei 1992), which is not applied to the data nor models. (b) Spectra from the single burst model at ages = 300 Myr (blue) and 12 Gyr (green), and the summation of the two (red). A correction for internal extinction ($A_V = 0.1$) was applied. The zero-points of the spectra (i.e., stellar masses) were adjusted by eye to approximately fit the observed FUV, NUV, B, V, R, and i magnitudes of the dwarf.

a physical companion of the spiral galaxy NGC 6503. Its structural properties are similar to those of the Local Group dwarfs. Integrated colors and resolved stars indicate a complex SF history not described by a single burst of any particular age nor by a simple continuous SF, which is also similar to the other known dwarfs (Weisz et al. 2011, 2012). The majority of the total stellar mass $\sim 4 \times 10^6 M_\odot$ is in an old stellar population. NGC 6503-d1 is the only companion galaxy of this magnitude near NGC 6503 within our field of view, about 1/6 of the virial radius. It is possible, and likely, that more dwarfs can be found in a future survey.

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